# Let The Dice Play God

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**Abstract**

We define life as the amplification of quantum uncertainty up to macroscopic scales. A living being is any amplifier that achieves this goal. We argue that everything we know about life can be explained from this idea. We study a ladder mechanism to estimate the probability that the amplification occurs spontaneously in nature. The amplification mechanism is so sensitive to small variations of its own parameters that it acts as a bifurcation itself, i.e. it implies that the universe is either everywhere dead or alive wherever possible. Since the first option is excluded by the existence of life on earth, we infer that the universe hosts a huge number of inhabited planets (possibly one per star on average). We also investigate models of conscious and unconscious learning processes, as well as the structure of the brain and evolution. Finally, we address the problem of creating artificial life.

## 1 The definition of life

The problem of explaining life is extremely complex. As of today, an accepted definition of life is still missing [1]. On the other hand, in the past century a huge progress has been achieved, both in physics and biology. For a physicist, in particular, it must be possible to understand life as a physical phenomenon. It is interesting to inquire whether the knowledge of the physical laws gathered so far is advanced enough to solve the problem or not. In this paper we argue that it is.

Although there is increasing evidence that the quantum phenomena play a non secondary role in the biological systems, there is no general agreement on the importance of such a role. That said, the starting point of the investigation we plan to carry out in this paper is the idea that quantum phenomena are actually the essential features of the living beings. We provide four main reasons to support this position.

The first reason is intuitive. Most phenomena related to life, such as evolution, and the behaviors of the living beings are not predictable, in contrast with the other phenomena that occur around us, which are deterministic. It might be argued that the unpredictability in question is a blunder, due to the extreme complexity of the physical systems that are involved. However, we know that pure chance does exist in nature, due to the uncertainty principle: at the microscopic level the output of a physical system cannot be predicted from the input, in general. Not only, but it is possible to amplify the effects of the uncertainty principle to large distances (which is what many experiments in quantum mechanics do). Since the amplification is possible, there is a definite probability that it may occur spontaneously in nature. It is scientifically interesting to estimate such a probability.

Thus, we think that linking the unpredictability of the living beings to quantum uncertainty is a natural hypothesis. It suggests to define life by means of quantum uncertainty and view a living being as an amplifier of quantum uncertainty up to the macroscopic relative distances.

The second reason we offer is encoded in the claim that everything we know about life can indeed be explained from this idea. Although the phenomena that have to do with life are extremely involved, we believe that in the following pages we clarify several critical issues and advance a lot in the direction of achieving this goal.

The third reason is even stronger. We claim that we can validate the idea *a posteriori*, by building artificial life along the guidelines that emerge from the investigation. Rather than plunging into a sterile and partisan discussion, we want to push for developing a new type of scientific research, whose final goal is to build artificially living creatures. We think that once we will be surrounded by artificially living companions – and it might not take so long –, any doubt about the ultimate nature of life will fade away.

The fourth reason follows from a result that we obtain, which we anticipate below.

Attempts to relate the uncertainty principle to biology or concepts like the so-called free will have appeared throughout the past decades. Although it is beyond the scope of this paper to examine the literature on these subjects in depth, some mentions are in order.

Important roles have been attributed to chance and unpredictability in biology by scientists and philosophers even before the advent of quantum mechanics. Well-known is the central role of chance in Darwin's theory of evolution, even if Darwin could not tell what the engine of chance was. For Maxwell, determinism was related to stability, while unpredictability and free will were related to instability, which he defined as the condition "when an infinitely small variation in the present state may bring about a finite difference in the state of the system in a finite time". In other words, he thought that instability is the "watershed, where an imperceptible deviation is sufficient to determine into which of two valleys we shall descend" [2]. For Nietzsche "there exists neither «spirit», nor reason, nor thinking, nor consciousness, nor soul, nor will, nor truth: all are fictions that are of no use" [3]. On the contrary, "it may be that our own voluntary acts and purposes are merely such throws" of dice [4].

After the discovery of quantum uncertainty, various scholars tried to link it to free will. Eddington thought that "the new physics thus opens the door to indeterminacy of mental phenomena, whereas the old deterministic physics bolted and barred it completely" [5] and "science thereby withdraws its moral opposition to freewill" [6]. Compton was convinced that "there are, however, conditions under which the uncertainty in a small scale event may result in an equal uncertainty in an event of great magnitude" [7]. He thought that, "as far as physics is concerned, a person's actions which we think of as free would thus appear to occur simply according to the rules of chance" [8]. However, he also thought that the principle of uncertainty was not sufficient to prove freedom. He said that, instead, "something additional to the physical phenomena is involved", because "freedom does, however, involve the additional determining factor of choice, about which science tells us nothing" [8]. Popper shared many of Compton's views. He admitted that "it is conceivable that something like the amplification of a quantum jump may actually happen in our brains if we make a snap-decision", but was against the "doctrine according to which the alternative to determinism is sheer chance", stating that "freedom is not just chance" [9].

More recent studies concentrated on human consciousness and the question whether it can be explained by the physical laws as a weakly emergent consequence of the brain activity or it requires more [10].

In our opinion, the main flaws of these investigations and proposals are that they are human centered, unsystematic and not particularly ambitious. They do not aim at understanding life, but focus on particular aspects of the human life. We would like to pursue an investigation that is not influenced by the existence of humans in the universe. In this spirit, we take a vow to basically ignore the human beings and their emotional needs and quests for moral principles, to concentrate on the possibility of developing a new science.

To summarize, we view quantum uncertainty as the "elementary bit of life". Precisely,

*a*) life is the amplification of quantum uncertainty to macroscopic scales;

*b*) a living being is any structure that amplifies quantum uncertainty up to the macroscopic scales.

When the amplification occurs spontaneously in nature, it generates natural life. When it is produced by the human beings, it generates artificial life.

Among the other things, we study the probability that the amplification occurs spontaneously in nature. It turns out that, without a ladder amplification mechanism (LAM), such a probability is so small that the universe would have to be everywhere dead. Since we exist, nature must be equipped with one or more ladder mechanisms that facilitate the amplification by subdividing the process into a sequence of reasonably small steps. We show that the LAM is so sensitive to small variations of its own parameters that it implies that the universe is either everywhere dead or alive wherever possible. Since, again, the first option is excluded by the existence of life on earth, we conclude that the universe must host a huge number of inhabited planets. This result offers a fourth reason in support of the idea that life is the amplification of quantum uncertainty to macroscopic distances: a reduced role of quantum uncertainty can be viewed as a huge variation of the parameters of the LAM, which would depress the probability of spontaneous life formation from one down to zero.

It may be observed that any device we build to make experiments of quantum mechanics, such as the Stern-Gerlach experiment, the double-slit experiment, or any quantum random number generator, amplifies quantum uncertainty up to macroscopic distances. The definition of life we have given implies that such devices are "alive", in the moment they make measurements. This idea might sound unappealing to some people. However, we do not see a compelling reason to refine (and possibly burden) the definition of life to prevent this "risk". A refinement, even if well framed, could easily lead to a lack of clarity. Moreover, as explained already, what is unsatisfactory to humans is not going to influence our investigation. After all, evolution tells us that we are descended from primates and simpler species, so it should not be that upsetting to discover that we are actually descended from the atom.

It goes by itself that we do not consider the reproductive ability a defining property of life. Indeed, a sterile living being must still be considered alive. Nevertheless, the reproductive ability is important to sustain and expand organic life, because generating a large number of individuals rapidly enough makes it possible to have selection, adaptation and evolution. At the same time, there might be different forms of artificial life and some of them may not need a reproductive ability. Certain types of artificially living creatures may be practically eternal. They might learn how to *produce* other individuals (rather than *re*produce) or upgrade/evolve their own bodies. In that case, the number of individuals might not be crucial to have evolution and/or prevent extinction.

The paper is organized as follows. In section 2 we describe some basic quantum devices and discuss how they can be combined. In section 3 we estimate the probability that the right combinations of quantum bifurcations form spontaneously in nature, with the help of a ladder amplification mechanism. In section 4 we investigate models of conscious and unconscious learning processes. In section 5 we study the structure of the brain and some of its basic functions. In section 6 we describe the mechanisms of reproduction and evolution. In section 7 we address the problem of creating artificial life. Section 8 contains the conclusions.



## 2 Chains of quantum bifurcations

Before dealing with more complicated issues, it is convenient to describe some basic quantum systems and the simplest ways of combine them.

Consider a spin-1/2 particle. Let $\mathbf{s}$ denote the spin operator and $s_i$ its component along the $i^{th}$ direction. Let $|+,i\rangle$ and $|-,i\rangle$ denote the eigenvectors of $s_i$ with eigenvalues $+1/2$ and $-1/2$, respectively. Let $Q_0$ denote a device that measures the spin component of input particles $|+,x\rangle$ along the $z$ direction. The states of the output particles are $|+,z\rangle$ and $|-,z\rangle$ with equal probabilities $P^+ = P^- = 50\%$. We call this system a quantum bifurcation.

Now, let $\hat{\alpha} = (\cos\alpha, 0, \sin\alpha)$ denote the versor of the $xz$ plane that forms an angle

$\alpha$ with the $x$ axis. Let $|+,\alpha\rangle$ denote the eigenstate of the operator $s_\alpha \equiv \mathbf{s}\cdot\hat{\alpha}$ with eigenvalue $+1/2$. For example, states $|+,\alpha\rangle$ can be obtained from states $|+,x\rangle$ by letting the particles cross a uniform magnetic field oriented along the $y$ axis. Let $Q_\alpha$ denote a variant of the system $Q_0$ that measures the spin component of input particles $|+,\alpha\rangle$ along the $z$ direction. The outputs of $Q_\alpha$ are still $|+,z\rangle$ and $|-,z\rangle$, but now their probabilities are $P_\alpha^+ = (1+\sin\alpha)/2$ and $P_\alpha^- = (1-\sin\alpha)/2$, respectively. For example, $\alpha = 30^0$ gives $P^+ = 75\%$ and $P^- = 25\%$.

A device $H$ that is able to operate the modification $Q_0 \to Q_\alpha$ is a simple tool that can be used to fine tune the output probabilities to favor an output over the other output.

Another elementary quantum device can be imagined as follows. Consider an atom A and call $E_0$ and $E_1$ its first two energy levels (which we assume to be non degenerate), corresponding to the states $|0\rangle$ and $|1\rangle$, respectively. Let $\tau$ denote the lifetime of the state $|1\rangle$. If A is isolated and its state is $|1\rangle$ at time $t=0$, the probability that A decays to $|0\rangle$ within an amount of time equal to $t$ is

$$p(t) = 1 - \mathrm{e}^{-t/\tau}. \tag{2.1}$$

Now, assume that the atom A is initially in the state $|0\rangle$ and interacts with a radiation of intensity $I$, with a spectrum of frequencies peaked around $\omega = (E_1 - E_0)/\hbar$. The probability that the atom is excited to the state $|1\rangle$ within time $t$ is

$$w(t) = BI\tau^*\left(1 - \mathrm{e}^{-t/\tau^*}\right), \tag{2.2}$$

where $B$ is the Einstein coefficient and $\tau^* = \tau/(1+2BI\tau)$.

Build a quantum device, still denoted by $Q_\alpha$, as follows. Assume that A is in $|0\rangle$ at $t=0$ and interacts with the radiation for an amount of time $\Delta t$ such that $w(\Delta t) = \bar{w}$, for a given $\bar{w}$. After that, the atom, if excited, goes back to the fundamental level with the decay probability (2.1). Let $\Delta\bar{t} = -\tau\ln(1-\bar{p})$ denote the amount of time such that $p(\Delta\bar{t}) = \bar{p}$, for a given $\bar{p}$. Assume that, if the atom does not emit a photon within $\Delta\bar{t}$, the device $Q_\alpha$ discards the event and starts over. Instead, if the atom emits a photon, $Q_\alpha$ records the answer "yes", if the emission occurs before the threshold

$$\Delta t_\alpha = -\tau\ln\left(1 - \bar{p}P_\alpha^+\right) \tag{2.3}$$

[which is such that $p(\Delta t_\alpha) = \bar{p}P_\alpha^+$] and "no" if the emission occurs after $\Delta t_\alpha$. In the end, the output "yes" has probability $P_\alpha^+$ to occur, while the output "no" has probability $P_\alpha^-$. Modifying $\alpha$ and the threshold $\Delta t_\alpha$, the probability of outputs can be tuned to favor one or the other answer.

The systems $Q_\alpha$ are typical elementary quantum devices. What is interesting, now, is to inquire what happens when large numbers of them are combined into complex systems. It is not necessary to require that each unit $Q_\alpha$ projects onto a pure state. Actually, it is more interesting to have patterns of entangled devices, as naturally occurs in liquids.

In simple terms, the microscopic quantum systems $Q_\alpha$ can be combined in two basic ways: at random or in ordered sequences. When they are combined at random, the effects of the uncertainty principle average to zero and the result is an apparent determinism. When they are combined in an ordered sequence, the effects of the uncertainty principle can be amplified at will to macroscopic scales. In simple terms, the random combinations give rise to the nonliving portion of the universe. The ordered combinations originate life.

The random combinations, where the elementary systems are distributed with no particular rule, are by far the most probable ones in nature. The simplest example is a system made of $N$ copies of $Q_0$, whose global output is the average of the $Q_0$ outputs. If $N$ is large, the mean value of the $z$ component of the spin of the output particles is equal to zero, with a normal probability distribution. This means that the system loses the ability to make a decision.

A combination in ordered sequence, on the contrary, is a configuration in which the outcome of a single quantum bifurcation affects the external world or the nearby bifurcations. For example, the output of a device $Q_0$ can be used to modify the next device $Q_0$ of the sequence by turning it into a $Q_\alpha$ or a $Q_{-\alpha}$, where $\alpha$ is fixed amount. Arbitrarily complex patterns, chains, trees, or circuits, can be built, increasing the variety and complexity of responses at will.

Locally, and in a very small fraction of cases, the microscopic quantum systems can spontaneously combine into ordered sequences, and amplify the effects of quantum uncertainty to macroscopic scales. We claim that the human beings, as well as the other living beings, animals and plants, are examples of such spontaneously formed quantum amplifiers. The rareness of life in the universe gives us an idea of how small the probability of spontaneous formation is. At the same time, the presence of life in at least one planet ensures that it is nonvanishing. In the next section we estimate that probability and show that interesting things come out from this kind of investigation.



## 3 From atoms to cells: the LAM

In this section we study the probability that the right combinations form spontaneously in nature.

Let us begin by recalling a few numbers. The size of the atom is about $10^{-8}$cm. It can be taken as the microscopic scale of the quantum phenomena. A cell is already a well organized system, and in most cases a living being in itself. The typical size of a cell is $10^{-3}$-$10^{-5}$cm in the case of prokaryotes and $10^{-3}$-$10^{-2}$cm in the case of eukaryotes [11], which are made of about $10^{14}$ and $10^{11}$ atoms, respectively. We can take $10^{-5}$cm as a measure of the macroscopic scales where organic life is present in form of cells. Eukaryotes are cells with nuclei, while prokaryotes are cells without nuclei. Various structures without cells are capable of replicating themselves, autonomously or non autonomously: the viruses (virions), which have a DNA; the viroids, which have an RNA but no DNA; the prions, which are just proteins. The DNA is a macromolecule made of about $10^{8\text{-}11}$ atoms in eukaryotes, $10^{7\text{-}8}$ atoms in prokaryotes and in viruses [12]. The DNA is organized in relatively simple small units, the nucleotides, which contain about 35 atoms each. There are viruses with a DNA made of just 1821 nucleotides [13].

The number of atoms in the observable universe is about $N_U = 10^{80}$, distributed in about $10^{23}$ stars [14]. The universe contains also matter of different nature, like the dark matter, which might also be able to form life of some type. Nevertheless, the dark matter in the universe is "just" 4-5 times more abundant than ordinary matter. For the purposes of this paper, including or neglecting the dark matter does not make a great difference, since numerical factors of order 1 cannot be estimated anyway. Thus, a reasonable work hypothesis is that the matter of the universe is made of $10^{80}$ "atoms" in total.

A typical star, like the sun, has $10^{57}$ atoms. The planet earth has $10^{50}$, while Jupiter has $10^{54}$. The amount of living matter on earth can be calculated as follows. Prokaryotes are made of about $10^{30}$ cells [15], which means roughly $10^{41}$ atoms. The eukaryotes contribute by an amount that is similar to the one of the prokaryotes (with a predominant role of plants), while the contribution of viruses is smaller by a factor one hundred [16]. Thus, we can assume that life on earth is made of $10^{41}$ atoms in total. For comparison, the human population is around $6 \cdot 10^9$ people, which means $10^{23}$ cells, i.e. about $10^{37}$ atoms.

Not all the atoms $N_U$ of the universe are in the condition to generate life. In particular, the four phases of matter, solid, liquid, gas and plasma, do not equally favor the formation of ordered sequences of quantum bifurcations. Solids are not dynamic enough, while gases and plasmas are not stable enough. Liquids have the desirable properties to enhance the search for the right combinations, although they may not stabilize them once found. In the body of a living being there are both liquid and solid phases, so it is reasonable to restrict to the portion of the universe where these two phases are in contact with each other.

To estimate the fraction of atoms that can effectively generate life, we multiply by reduction factors that take care of various restrictions. First, we exclude the atoms that make the stars, as well as the gaseous or inhospitable planets. To do so, we multiply $N_U$ by a fraction equal to the ratio $10^{-7}$ between the number of atoms that make the earth and those that make the sun. This corresponds to assume that there are roughly $10^{23}$ planets earth in the universe - one per star. We are not assuming that life is effectively present in all of them, at this level. After the reduction we get $N'_U = 10^{73}$.

Then, we multiply by the ratio $10^{-9}$ between the numbers of atoms of the earth and the number of atoms contained in the bodies of the terrestrial living beings, which leads to $N''_U = 10^{64}$ atoms of potentially living matter in the universe.

Most parts of the body of a complex living being behave deterministically. Nevertheless, we have shown above that most living beings are unicellular, like the prokaryotes, so there is no need of a correction factor for this effect. Moreover, it is reasonable to think that all the cells of the living beings amplify quantum uncertainty to some degree, even those that are part of organs that on average appear to behave deterministically.

Let us now consider the combinations of atoms that amplify the effects of quantum uncertainty. For simplicity, we study one-dimensional sequences. The atoms must be appropriately oriented, because otherwise quantum effects average away. We call "in series" the orientation that amplifies the quantum effects and "in parallel" the orientation that suppresses them. Call $p$ the probability that two close atoms are oriented in series. Then $p^N$ is the probability that a row of $N$ atoms amplifies quantum effects to the scale $d_N = N \cdot 10^{-8}$cm.

Assume that the atoms can be described as cubes. Two adjacent cubes have one face in common and each cube can face the next one in 6 different ways. Thus, we take $p = 1/6$. Then, consider a row of $N = 10^3$, which is enough to cover the diameter of the cell of a simple prokaryote. The probability of formation of the ordered sequence is

$$p^N \sim \left(\frac{1}{6}\right)^{10^3} \sim 10^{-778}, \tag{3.1}$$

i.e. an unbelievably small number. If we take $p = 1/2$ the situation does not improve much, since we get $p^N \sim 10^{-301}$.

Assume that, since the birth of the universe all the atoms $N_U$ have been making attempts to search for the right combinations at a speed $V$ of one billion attempts per second per atom. This means that $VT_U$ attempts have been made so far by each atom, where $T_U$ is the age of the universe. We also assume that, once the right combination is found, it lasts forever. We round $T_U$ to $10^{17}$s (a quarter of the actual age), because we are interested in orders of magnitude and also because $10^{17}$s ago is more or less when the earth formed and became inhabitable. Then, by now, we would have

$$N_U\left[1-(1-p^N)^{VT_U}\right] \tag{3.2}$$

right sequences of $N$ atoms in the universe[1]. The formula gives $10^{-672}$ with $N = 10^3$ and $p = 1/6$. It does not make a big difference if we use $N_U''$ instead of $N_U$, or $p = 1/2$ instead of $p = 1/6$, or $4T_U$ instead of $T_U$: the result is practically zero, so this kind of amplification mechanism is just hopeless.

The outcome changes a lot if we assume that there is a *ladder amplification mechanism* (LAM) in nature. More precisely, assume that the amplification effort is split into $n$ separate steps, or rounds, each of which takes an amount of time equal to $T_U/n$. In the first round, atoms organize into structures $s_1$ of $\ell$ atoms. In the $i$-th round ($i = 2, \ldots n$), $\ell$ copies, or versions, of the $(i-1)$-th structure $s_{i-1}$ combine into the $i$-th structure $s_i$. Then, after $n$ rounds we have structures made of $N_C = \ell^n$ atoms. More complicated LAMs can be studied (for example, with different $\ell_i$s for different rounds), but here we just choose the simplest option to prove the main point. We still assume that the right configurations, once formed, are stable. If $V$ attempts are made per second per structure, the probability of finding the right combinations of $N_C$ atoms is

$$P(N_c, n) = \left[1-(1-p^{N_C^{1/n}})^{VT_U/n}\right]^n. \tag{3.3}$$

As said, we have assumed that the right combinations are stable, which is not so obvious. Actually, the most stable combinations are the "wrong" ones, those that make the nonliving portion of the universe, which is made of $N_U - N_U''$ atoms. An effective stability for the right combinations can be achieved by means of reproductive mechanisms. We have to assume that, at some point, there appear combinations that can reproduce themselves sufficiently rapidly to ensure self-sustainment. Then, those combinations can be assumed to last forever (in the sense that they generate a sufficient number of similar new combinations before the old ones die). In the simple model considered here, this requirement is incorporated in the probability $p$.



[1]Formula (3.2) is obtained as follows. The factor $N_U$ is the number of sequences that can be built with $N$ atoms. We can imagine, for example, that all the $N_U$ atoms are aligned along a circle. The factor $1-(1-p^N)^c$ is the probability that a sequence is right after $c$ attempts. For $c = 1$ we have $p^N$. For $c = 2$ we have $p^N + (1-p^N)p^N$, which is the sum of the probability to have it right after the first attempt, which is $p^N$, plus the probability to have it wrong in the first attempt and then right after the second attempt, which is $(1-p^N)p^N$. For $c = 3$ we have $p^N + (1-p^N)p^N + (1-p^N)^2p^N$, etc. For $c$ generic (3.2) is easily obtained.

If we take this into account, the probability of finding a living being made of $N_c$ atoms is then

$$P=\sum_{N_c,n} P(N_c,n) f(N_c,n), \qquad (3.4)$$

where $f(N_c,n)$ is 1 or zero, depending on whether the right combinations can reproduce themselves sufficiently rapidly or not. Ultimately, the correction just selects the right $N_c$ and $n$ (assuming that they exist). With those values the estimates obtained from formula (3.3) make sense.

Another assumption tacitly made to derive (3.3) and (3.4) is that, once formed, the structures $s_{i-1}$ are close enough to one another, so that they can effectively combine into the $i$-th structures $s_i$. This assumption can be incorporated into corrections to the velocity $V$ and/or the probability $p$. We can also justify the assumption *a posteriori*: if the final probability $P$ turns out to be zero, the actual result cannot be worse than that. If $P$ turns out to be 1, it means that all the structures that can potentially form do form, so it is plausible that they are located at convenient distances from one another without having to change $V$ and $p$ too much.

With $\ell=20$ and $n=10$ steps, $\ell^n$ is approximately the number $N_C=10^{13}$ of atoms of a cell. If we assume that the velocity $V$ is 1 per hour per atom, we get $P=10^{-31}$ for $p=1/6$ and $P=1$ for $p=1/2$. With $\ell=10$ (roughly, the number of atoms of a base), $n=13$ steps and the same velocity $V$, we get $P=1$ for $p=1/6$. With $p=1/6$, $\ell=10$, $n=13$ and $V=1$ per year per atom, we get $P=80\%$. Probabilities equal to one or close to one mean that all or almost all the $N_U''$ atoms that are effectively capable of generating life do achieve that goal, leading, on average, to about one inhabited planet per star.

The probability of each step of the LAM is

$$F(p,\ell,c)=1-(1-p^\ell)^c,$$

where $c=VT_U/n$. The crucial quantity that controls $F$ and the final outcome $P$ is

$$\chi=cp^\ell,$$

which we call *root* of the LAM. Since $c$ is large, it is sufficient to have $\chi \gtrsim 1$ to obtain $F\sim 1$, $P\sim 1$, because

$$F=1-\left(1-\frac{\chi}{c}\right)^c \underset{c\rightarrow\infty}{\rightarrow} 1-\mathrm{e}^{-\chi}.$$

On the other hand, if $\chi$ is small, then $F\sim\chi$, so $P$ is also small.

It is hard to have $F$ and $P$ reasonably different from zero if, say, $\ell>$ 20-30. For example, with the last used values for $p$, $T_U$, $n$ and $V$, $F(p,\ell,c)$ is equal to $5\cdot 10^{-8}$ for $\ell=20$ and $2\cdot 10^{-23}$ for $\ell=40$.

We learn that the most important quantity is $\ell$, which should be reasonably small. Amplification steps of $\ell = 10$ are affordable in nature, but bigger steps become problematic. On generic grounds, if even one step of the LAM requires an amplification factor $\ell$ greater than 20-30, then the probability $P$ becomes too small to explain the appearance of life. In the alternative, $p$ is also important. Instead, we cannot raise low values of $F(p, \ell, c)$ too much by playing with $c$.

The natural question is then: is organic life equipped with a suitable LAM? The ladder of organic life could be made of atoms, molecules, macromolecules, then (relatives, variants or ancestors of) ribozymes, prions, RNA, virions, DNA and viruses, finally prokaryotes, unicellular eukaryotes, multicellular eukaryotes.

It is enlightening to turn the argument around. There is no hope to explain the appearance of the shortest known DNA (1821 nucleotides), or a combination of $\ell = 1000$ elements, or even a combination of just $\ell = 100$ elements, by means of a single amplification step (i.e. a jump from separate elements to a structure of 100 elements), not even by having each element make a billion trials per second for the whole lifetime of the universe. This means that nature *must* be equipped with the required ten or so steps with $\ell \sim 10$ that make the amplification possible, otherwise life would have never appeared, not even on a single planet in the whole universe. In conclusion, it might be early to identify the LAM of organic life with precision, but we know that it must exist.

Moreover, we have seen that small variations of the input parameters of the LAM lead to huge variations of the outcome, which switches very quickly from a universe that is everywhere dead to a universe that is alive wherever possible. Any intermediate situation is banned, because it would require very unnatural fine tunings. Basically, the LAM is itself a bifurcation, which allows only two outcomes: $P = 0$ and $P = 1$. Since the universe is not everywhere dead, because we exist, we can exclude $P = 0$. This leaves just $P = 1$, which means that the universe is alive everywhere possible.

The conclusion is that there must be life on all the planets that permit it, which might even mean one planet per star on average. Even if it were just one planet per hundred thousand stars, there would still be billions of billions of inhabited planets in the universe.

One may wonder whether something resembling life (say, an amplification of chance due to thermal noise, chaotic systems, statistical fluctuations and so on) might be achieved without quantum uncertainty, i.e. assuming that, for all the purposes of studying life (its functions, origin and evolution), we can treat the atoms and the molecules, as well as the DNA, the cells and the living beings, as deterministic systems. In this scenario, what appears to be unpredictable about the phenomena of life is just a blunder, as in simulations due to pseudo random number generators. The strongest objection against this possibility comes precisely from the results we have just found. Indeed, we have shown that a small variation of the parameters involved in the LAM can change the outcome dramatically. Switching off quantum uncertainty, or downplaying its importance, is actually a huge variation of the parameters, since it implies that we must renounce the discreteness of the energy levels, the metastability of the excited levels, the quantum tunneling and all the other properties that are helpful to the interlocking mechanisms involved in the amplification, and presumably play key roles in allowing for mutations during the DNA reproduction. Then, the most obvious conclusion would be a universe that is everywhere dead, contrary to observation.

### 3.1 Death

The formation of structures that amplify quantum uncertainty to macroscopic distances requires a huge number of trials. How stable the structures are, once formed, depends on many variables. In a variety of circumstances, or after a sufficient amount of time, they can collapse back to disordered structures, which average quantum uncertainty away. This is death.

We may want to identify life as a phase of matter, which is very unstable at the local level (which refers to a single individual), but may be more stable at the global level (thanks to reproduction). The nonliving portion of the universe is another, much more stable, phase of matter. Death is the phase transition from the living phase to the nonliving phase.

As a physical phenomenon, life does not admit states of equilibrium, or cyclic behaviors. On the contrary, it can be "stabilized" only by means of a continuous renewal. Life can survive only if it has enough room to expand, grow, or evolve, which in most cases means explore new configurations and behaviors, using its built-in quantum trial-and-error processes. However, expansion, growth and evolution are possible only by a mechanism of learning and improvement, which in turn requires selection, which is possible only if there is instability and death.

Thus, the instability of quantum amplifiers at smaller scales is what speeds up the process of growth to bigger scales. It makes the expansion possible and ultimately tends to safeguard the existence of life for a longer period of time. There must be a sort of balance between instability and growth, since stability is possible only through the struggle for growth and growth is possible only through instability, by means of the reproduction/selection/death mechanism.

## 4 Q-learning systems

In this section we investigate models of conscious and unconscious learning processes. A Q-learning system $L$ is a structure able to

$i$) perceive from the outside world;

$ii$) make choices of quantum nature;

$iii$) act/react on the outside world;

$iv$) compare perceptions and evaluate them according to criteria;

$v$) modify itself;

$vi$) keep memory.

It may be helpful to imagine the Q-structure $L$ as made of smaller interconnected Q-units $U$, which function in a similar way at a smaller level, and possibly play different roles. We can assume that each unit can modify itself and/or modify other units or be modified by them. Together, the units can make arbitrarily large and complex Q-structures.

For simplicity, let us assume that a Q-unit $U$ can execute just two actions, $a_1$ and $a_2$, which are equally probable at the beginning. Briefly, $U$ perceives some signal $s$ from the exterior world, decides a reaction $r = a_1$ or $a_2$ to $s$, perceives the consequences of its reaction, in the form of another signal $s'$, evaluates whether the sequence $srs'$ is favorable or unfavorable, and finally modifies the probability distribution of $a_1$ and $a_2$ according to this judgment. Later, in a similar situation the same reaction will be more or less probable, according to the (supposed) advantage it brings to the Q-structure. This is how the system learns. At the level of the Q-structure $L$, the hardware modifications $Q_0 \to Q_\alpha$ can also be understood as a form of memory, or knowledge, or consciousness (see below).

For example, we can imagine that the decision devices of point $ii$) are made of systems $Q_0$, the actions $a_1$ and $a_2$ being triggered by the outcomes $|+, z\rangle$ and $|-, z\rangle$. Point $v$) can consist in the modification of $Q_0$ into a $Q_\alpha$, for a suitable $\alpha$. Assume that the reaction is $a_1$ and that its consequences are judged favorably, to the extent that $\alpha$ is tuned to 30°. The modified probabilities of the reactions $a_1$ and $a_2$ become 75% and 25%, respectively. Thus, when, at a later time, $U$ perceives a similar signal $s$, it more probably executes the same reaction $a_1$. If the consequences are still judged favorably (which is not to be taken for granted, since the judgment process is also of quantum nature, see below), the probabilities may become 90% versus 10%, etc. In this way, the unit $U$ learns whether an action is convenient or not.

The judgment of point $iv$) occurs quantum mechanically, by means of other devices $Q_\beta$, which may be provided by other units $U$. The criteria used for the judgment can be of various types. An important role, for life, is played by the criteria that aim at self-preservation. However, since life admits no equilibrium state, the only way to have a chance of self-preservation is by aiming at expansion. Thus, most criteria of point *iv*) judge the situations/modifications that lead to an increase of power favorably and all the others unfavorably.

Schematically, the learning system $L$ must contain a body $B$, a hardware developer $H$, an evaluation center $E$ and an action device $A$. The initial configuration of $E$ may be innate, but it can be modified by $H$. The body $B$ is a set of quantum systems $Q_{\alpha i}$, one or more than one for each type of known external signals, plus a number of unassigned systems $Q_0$ (or innately assigned systems ${Q_\beta}^{\text{inn}}$) that are ready to be associated with new types of perceptions. The body is also the memory where the responses to known signals and other informations are stored.

We have the scheme

$$\begin{array}{ccccccc} s & \longrightarrow & B & \longrightarrow & A & & \\ & & \uparrow & & & \searrow & \\ & & H & \longleftarrow & E & \longleftarrow & s' \end{array} \tag{4.1}$$

When a signal $s$ is perceived from the outside world, it is sent to $B$, which checks if it is of known type. If it is, a piece of information is already stored in the memory, and used to forward the signal to the appropriate quantum device $d(s)$. If $s$ is of unknown type, it is sent to an unassigned decision device, which becomes $d(s)$. The outcome of the assignment is stored in the memory.

The device $d(s)$ encodes the probability distribution of the quantum decision that is going to be made. The decision, in its turn, determines which action is executed by $A$. Call it $a(s)$. When the selected action $a(s)$ is executed, a corresponding information is stored in $B$. Then the learning system collects new external signals $s'$. If they are sufficiently close in time to $a(s)$, they are assumed to be responses to $a(s)$ (but this call is actually demanded to another decision center and possibly another learning system). The sequence $sa(s)s'$ is sent to $E$ for evaluation, to determine whether it is favorable or not. Finally, the hardware developer $H$ modifies the decision device $d(s)$ of $B$ to make sure that the reaction $a(s)$ becomes more or less probable, depending on the result of the $E$ evaluation. The data about the process are memorized in $B$.

More generally, $s$ can denote the context in which an initiative is taken autonomously, instead of an external signal of a specific type. In more sophisticated learning systems, $H$ can modify also $E$. Alternatively, the modifications of $E$, or its functions, may be demanded to other interconnected learning systems.

### 4.1 Consciousness and unconscious

In this paper, thought and consciousness, and several related concepts, such as freedom, intent, will, etc., are understood to have quantum origins. In particular, they are not exclusive qualities of human beings. Being conscious of the meaning of perceptions means having collected enough experiences to know how to react in order to produce favorable consequences and/or avoid unfavorable consequences. It goes without saying that many animals have consciousness. A dog, for example, can associate specific actions to human commands and other perceptions. When a dog becomes familiar with those perceptions and the consequences of its actions, we can legitimately say that it is conscious of them, in the sense that it knows which responses produce favorable consequences and which do not. At the same time, humans do not have consciousness in all the phases of their lives. For example, a newly born child is not conscious of the meanings of perceptions and actions. It takes months of work memorizing, associating and classifying, and executing actions and generating sounds autonomously, to reach a level where we can legitimately claim that the baby has acquired knowledge of the meaning of sounds and other perceptions, and has associated perceptions to actions and consequences. At that point, the baby is "conscious" of such things.

Thus, we can identify the learning scheme (4.1) as the conscious pattern. It can be summarized by the acronym SACEM (signal → action → consequence → evaluation → modification). Its main features are that it is "local" (we will understand in a minute what this means) and can be repeated an arbitrary number of times, to fine tune the probability distributions as much as possible and improve the learning.

Let us consider a large number $n$ of SACEM units and equip them with a global evaluation center $\mathcal{E}$ and a global hardware developer $\mathcal{H}$. The set of individual bodies $B_i$, plus possibly other structures that we do not need to specify here, make the global body $\mathcal{B}$. We obtain a pattern that, for the reasons that we are about to explain, can be described as the unconscious pattern:

$$\left.\begin{array}{c}\left[\begin{array}{ccccccccc} s_1 & \longrightarrow & B_1 & \longrightarrow & A_1 & & \\ & & \uparrow & & & \searrow & \\ & & H_1 & \longleftarrow & E_1 & \longleftarrow & {s_1}' \end{array}\right] \\ \vdots \\ \left[\begin{array}{ccccccccc} s_n & \longrightarrow & B_n & \longrightarrow & A_n & & \\ & & \uparrow & & & \searrow & \\ & & H_n & \longleftarrow & E_n & \longleftarrow & s'_n \end{array}\right]\end{array}\right\} \rightsquigarrow \; \mathcal{E} \; \rightarrow \; \mathcal{H} \; \rightarrow \; \mathcal{B} \qquad (4.2)$$

In what we are going to say, the local evaluation centers $E_i$ and the local hardware developers $H_i$ do not play important roles and in most situations can actually be absent. Then the SACEM units simplify to SAC units (signal → action → consequence) and the unconscious pattern becomes

$$\left.\begin{array}{c}\left[\begin{array}{ccccccc} s_1 & \to & B_1 & \to & A_1 & \rightsquigarrow & s'_1 \end{array}\right] \\ \left[\begin{array}{ccccccc} s_2 & \to & B_2 & \to & A_2 & \rightsquigarrow & s'_2 \end{array}\right] \\ \vdots \\ \left[\begin{array}{ccccccc} s_n & \to & B_n & \to & A_n & \rightsquigarrow & s'_n \end{array}\right] \end{array}\right\} \rightsquigarrow \mathcal{E} \to \mathcal{H} \to \mathcal{B} \tag{4.3}$$

We can distinguish a local level, which is the level of each SAC unit, and a global level, which is the whole structure. Let us concentrate on a SAC unit for the moment. When a signal $s$ is perceived, the memory stored in $B$ is interrogated, after which $s$ is forwarded to an appropriate or unassigned quantum device $d(s)$ of $B$. Then $d(s)$ determines an action $a(s)$. After $a(s)$ is executed by the action center $A$, its effects $s'$ are memorized in $B$. As before, $s$ can just be the context where an action $a(s)$ is autonomously executed. Instead of a trial-and-error mechanism, the SAC sequence describes a pure trial mechanism. It does not let the individual learn from its actions $a(s)$.

The SAC units are part of a more complex structure (like the brain), which also includes a global evaluation center $\mathcal{E}$, a global hardware developer $\mathcal{H}$ and a global body $\mathcal{B}$. At the right moment, the evaluation center $\mathcal{E}$ is activated. It gathers informations coming from a large number of individual bodies $B_i$ about their local experiences, occurred within a certain amount of time $T$. Then, it evaluates them at-large. On the basis of that evaluation, $\mathcal{E}$ instructs $\mathcal{H}$ to modify the probability distributions of the SAC units, or a large number of them. The data about the whole process are stored in the global memory of $\mathcal{B}$.

The crucial novelty here is that the operations of evaluation are not performed locally and instantaneously, as in the sequence SACEM, but on a collective scale, which means on groups of numerous SAC patterns at once, and delayed to a later stage (as in the dreams, the night activities of the brain, and so on). The delayed process of evaluation at-large makes it impossible, for the individual, to keep track of what happens with enough precision to become aware of it. The individual does change, the change being enacted by $\mathcal{H}$, but it has a hard time relating the change to its probable causes, so it perceives the change as unconscious, not wanted, automatic.

Despite the control we claim to have on our own lives, our conscious and unconscious activities presumably play equally important roles. What makes an activity "conscious" is that the evaluation of consequences occurs almost instantaneously, so it is possible to relate causes and effects and repeat similar SACEM patterns an arbitrary number of times, to refine the learning till it turns into an awareness. What makes an activity "unconscious", on the other hand, is that the evaluation is delayed and performed on a much larger scale. This makes each unconscious decision essentially unique and unrepeatable, because it is almost impossible to repeat the set of SAC patterns involved in it.

For example, an individual cannot consciously evaluate, as a whole, the enormous amount of choices made during an entire day. That is part of the job done by the unconscious part of the brain during the night. Similarly, the individual cannot plan its own changes of life. A change of life is a typical example of a decision that "just happens" and has cascade effects on all subsequent ones. It cannot be experimented, repeated or tested, since it is impossible to change life a thousand times to evaluate the huge number of available alternatives and develop a consciousness of what it truly means.

## 4.2 Remarks



Q-structures of arbitrary complexities can be built by combining the systems described above and create, for example, networks of interconnected Q-learning systems, where each unit evaluates and modifies the surrounding units. Such networks can collect, evaluate and memorize large numbers of experiences, and rapidly improve themselves by fine tuning the probability distributions to the responses that produce more favorable consequences. Presumably, the structures should be semiliquid, to ensure a better and faster adaptability.

At the same time, a learning process is so complex that it cannot be reduced to a small amount of simple operations. A newborn baby takes months to learn how to grab an object with its own hands without shaking and years to calibrate the movements enough to write and draw. This gives an idea of the challenges involved in the creation of artificial life.

In nature, learning and the ability of learning come with evolution, which is itself a long, involved trial-and-error process. However, there are no absolute notions of "error" and "success": what is an error in a context or environment may be the right answer in a different context or environment. Lowering the probability of errors (i.e. downplaying the role of quantum uncertainty in favor of more determinism), lowers the possibility of adaptation. By the arguments of the previous section and the high sensitivity of the LAM to its own inputs, this can easily turn the probability of life formation and self-sustainment from one down to zero.

The main implication of these facts is that, in the quest for building artificial life (see section 7), the largest possible amount of functions of the Q-structures should be demanded

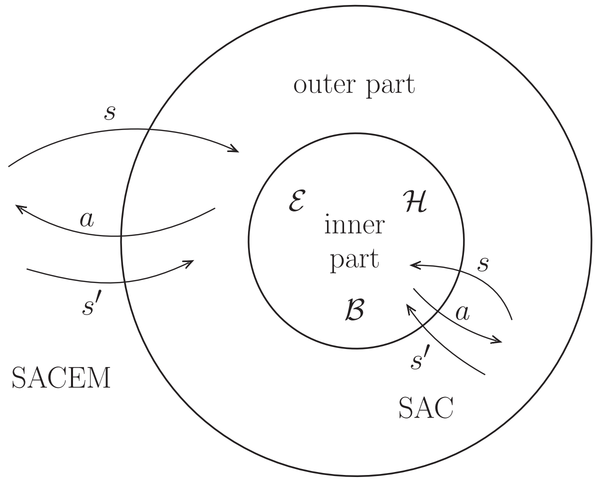


Figure 1: Basic structure of the brain

to quantum uncertainty, because a more deterministic structure may appear to be more powerful in the short range and in a specific environment, but is doomed to get extinct quite easily.

## 5 Brain

As said, arbitrarily sophisticated structures can be built, able to recognize perceptions, make decisions, elaborate actions, learn from the consequences of their own actions. The outcome is what we can call an organism, with a structure that is partly innate, due to evolution, and partly acquired by means of learning and experience, thanks to the internal modifications occurred during the course of life.

A rich structure of elementary quantum bifurcations, ordered and hierarchically organized, is the brain. We can imagine it as made of two main parts, as shown in fig. 1. The inner part, which is unconscious, is mainly made of patterns of type SAC and hosts the global evaluation center $\mathcal{E}$ and the global hardware development center $\mathcal{H}$. The outer, conscious part is mainly made of patterns SACEM. The global body $\mathcal{B}$ is the union of both parts. Each part is hierarchically organized into levels, sublevels, and so on.

The outer part of the brain receives signals from the external world as well as itself and performs actions on the external world. The inner part, instead, receives signals from the outer part and performs actions on the outer part as well as itself (with some exceptions, considered below). The internal perceptions are the sensations of activities within the brain. They allow the inner part to perceive the outer part. They can also make different sectors of the outer part perceive one another.

Basically, the actions of the inner part influence or permanently modify the probability distributions of the decision devices that are located in the outer part. They can reconfigure and reorganize the outer part to a high degree.

The two-part structure of the brain, where only the outer part acts on the external world, lets the individual reach a considerable level of self control and enact smooth behaviors, after a due amount of learning experiences. A child needs several years of adult supervision and interactions with the external world to achieve this goal. Once the outer part of the brain is well structured, the behaviors of the individual start to "make sense". That said, they never become deterministic, since predicting a decision of a living being remains impossible in principle due to its intrinsic quantum nature.

In general, an external signal, once it becomes a perception, has the effect of proposing a sort of "question" to the brain, and can reach a certain level or depth in its structure, which depends on the features of the signal, among which its intensity and duration. Decisions of superior levels may have cascade effects on the inferior levels. If a signal has particular features or is sufficiently strong (humor, fright, terror, adrenaline rush or excitement due to gambling, extreme sports, etc.), or repeated and long (chronic pain, depression), it can reach also the inner part, including its superior levels. Then its cascade effects on the inferior levels and the outer part may generate decisions that are commonly rather disfavored, such as committing a suicide. In other situations they can lead to a change of life.

In pathological cases, adults may loose the ability to control their behaviors. Certain forms of mental problems are probably due to shortcuts in the brain structure, where the unconscious patterns of the inner part act directly on the external world, bypassing the operations of filtering enacted by the outer part. The resulting behavior appears inexplicable, possibly schizoid. In reality, it is "just" the consequence of randomly generated decisions of quantum nature, whose probability distributions have remained flat in large regions, because they have not been fine tuned.



## 5.1 Will

The brain considers an action $a(s)$ as "wanted", "predetermined", "intentional", when it has already been decided by the quantum systems $d(s)$ assigned to it, but it has not been executed, yet. This internal sensation is the will. It involves interconnected SACEM structures in the outer part of the brain.

Previously, we used the symbol $a(s)$ to denote both the outcome of the decision device $d(s)$, located in the body $B$, and the consequent action executed by the action device $A$. We tacitly assumed that there was no time delay between the decision and the action. In the present discussion, such a delay plays a key role, in particular in the human being. We can define the intentional action $a_{\rm in}(s)$ as the outcome of the decision device $d(s)$ and distinguish it from the executed action $a(s)$. The intentional action is stored in a suitable sector of the memory contained in $B$, till it is executed. Before that, a change of mind can interfere and make the individual execute a completely different action.

The will is the (internal) perception of the intentional actions $a_{\rm in}(s)$ stored in the memory. Since there is no way to perceive a quantum process $d(s)$ *while* it determines its choice $a_{\rm in}(s)$, the best the brain can do is associate an internal perception with a choice that has already been determined. This is precisely the will. During the time interval that separates the quantum decision $a_{\rm in}(s)$ from the effective action $a(s)$, the decision $a_{\rm in}(s)$ is classified as intentional. After $a(s)$ is executed, the brain continues to consider the action as intentional, as long as it remembers that it was intentional. The time delay interposed between $a_{\rm in}(s)$ and $a(s)$ gives the illusion of awareness, intent, consciousness, control on the actions.

A decision may also be equipped with the internal perceptions of certain activities that have contributed to shape the probability distributions that lead to it (such as the "thoughts"). It is nevertheless important to stress that will, free will, consciousness, awareness, intent, reason, intellect, etc., do not corresponds to elementary physical phenomena. They are not concurrent *causes*, or *sources* of a decision (because no such causes exist in nature), although they are normally misunderstood as such. Instead, they are the results of large numbers of combined random processes, applied in various ways and different forms. Because the origin of such random processes is of quantum type, all decisions are ultimately consequences of quantum uncertainty. Will and intent do not *make* decisions: they are the first internally perceived sensations after the decisions have already been made, quantum mechanically, by the devices of the brain, before those decisions are turned into effective actions.

## 5.2 Pain and pleasure

Pain is a compulsory distraction that prevents a living being from executing intentional actions. When an individual hurts itself, superior levels of the brain, mostly unconscious, are activated. Their decision centers, characterized by peaked probability distributions, make certain reactions (like the reactions to a danger) almost compulsory, bypassing will, consciousness, intent and the whole outer part of the brain. Exceptionally, the inner part of the brain acts directly on the external world. In such a situation, all previously determined, intentional decisions are overruled. The individual is forced to suddenly turn its attention from a "wanted" direction to a "non wanted" one. An individual that is subject to such a distraction *suffers*. Similarly, pleasure is the sensation associated with the presence of anything that helps executing intentional actions.

# 6 Reproduction, evolution, intelligence

The ordered sequences of quantum bifurcations that amplify the effects of quantum uncertainty to the macroscopic scales are statistically disfavored, so the living phase of matter is intrinsically unstable and ephemeral. Reproduction is a possibility, presumably not the only one, that can extend the duration of the living phase. The reproductive ability is one of the first consequences of evolution, in the known life forms, although it is not the engine of life.

Evolution can be described by the unconscious pattern (4.3). The global body $\mathcal{B}$ is the species and the global hardware developer $\mathcal{H}$ is reproduction. The global evaluation criterion $\mathcal{E}$ is natural selection. Within the SAC units, the context $s_i$ is (typically) the encounter of two individuals (the mother, the father), the action $A_i$ is the mechanism of DNA replication and the birth of new individuals, the consequence (new context) $s_i'$ is the set of parents and newborns, i.e. the family, the body $B_i$ is the set of individuals interested in the process (the parents at first, the family at last).

Evolution can also be viewed as a learning process. A new individual, whose innate structure is different from the innate or improved structures of its parents, is a sort of trial of a trial-and-error mechanism. Many individuals turn out to be "errors" and the fittest ones survive. This way, the mechanism of evolution allows the species to acquire a form of knowledge of the surrounding environment. In the simpler species, this kind of knowledge is gathered very quickly, as in bacteria and many insects, where few individuals are able generate huge numbers of new individuals and so adapt quite rapidly. In more complex species the process of learning by evolution is much slower.

In addition, the human beings have developed intelligence. Intelligence and evolution can be seen as two ways of learning, with similarities and differences. In particular, they are both trial-and-error mechanisms of quantum origin, in one case concentrated inside a single individual, in the other case organized at the level of the species. We can associate intelligence with the conscious pattern (4.1), while, as said, evolution follows the unconscious pattern (4.3). Although intelligence plays important roles in several situations, we think that it is a minor aspect of life, in the big picture, which is the reason we do not spend many words about it in this paper.

## 7 Artificial life

The living beings and the nonliving portion of nature are ultimately made of the same ingredients, differently combined. It is conceivable that several types of life forms, besides the organic one, exist in the universe. It is also interesting to explore the possibility of creating some new life forms artificially, by amplifying quantum uncertainty to the macroscopic scales along the lines explained so far. The present knowledge and resources of the human species suggest that this task is within reach, although it may require a considerable collective effort. Learning how to build and work with liquid or semiliquid devices is extremely helpful, as is arranging huge amounts of quantum random number generators in tiny spaces. In a due amount of time, we might be able to equip the "$Q$-beings" or "$Q$-droids" with the ability to reproduce, or produce themselves. Once that goal is achieved, the Q-droids can proceed by themselves, through the mechanisms of selection and evolution, and, if they are versatile enough, survive for a long time.

The arguments of the previous sections have been phrased with an eye at the final goal we have in mind, which is precisely the creation of artificial life. At this point, the conclusions are more or less straightforward.

The program of creating artificial life can proceed along three main directions. The first direction is to construct simple, possibly small, non specialized but very versatile $Q$-beings. At the beginning the $Q$-droids could be sold as $Q$-toys ($Q$-dolls, $Q$-worms, $Q$-tamagotchis, $Q$-pets, $Q$-companions, etc.). In passing, let us note that this business may turn into a huge success, because it will likely help reduce the loneliness of people in our societies. The tiniest $Q$-beings could be even sent to explore the universe for us.

The second possibility is to build more specialized $Q$-droids and equip them with a good deal of built-in knowledge, which might include the ability to produce other $Q$-droids similar to them. From their perspective, the built-in knowledge would be innate and would save them a lot of learning effort. Their behaviors would look less erratic and much more under control from the beginning. These $Q$-beings will better fit into the environment in the short run, but will be less versatile and have fewer possibilities to adapt themselves in the long run, when important changes will eventually occur. This direction for artificial life may have some interest if the $Q$-beings are built to be basically immortal.

We mention a third, easier way to investigate the amplification of quantum uncertainty to macroscopic scales, although it is of a rather different type: creating one-dimensional and two-dimensional $Q$-beings, such as sophisticated software programs for decision making, money investments, trading, politics, artificial intelligence, etc.

The creation of artificial life is demanding also because it requires to break with some common ways of thinking. In particular, it is not supposed to make us humans more powerful, or happy, or live longer, or be healthier. In some sense, it is meant to be a very "altruistic" research, directed to build life forms that can turn out to be more powerful than ours, compete with us for the control of the world and possibly overthrow their own creators. Through evolution, many species have achieved the goal of creating more powerful, fitter species. However, none of them has done it intentionally, at least so far.

The creation of artificial life is the next step of the amplification of quantum uncertainty. Clearly, such a step does not easily fit a LAM mechanism like the ones considered in section 3. Likely, most artificial life forms to be created by us have no chance to appear spontaneously in nature. In a way, they belong to the class of "impossible LAMs". However, nature seems to have found the way to bypass this difficulty: create intelligent species of organic life to take the plunge toward otherwise unreachable forms of life.

## 8 Conclusions

After a century of research in quantum mechanics, we can fairly say that the phenomena that take place at the atomic scales (and below those) have become familiar to us. Unless something has escaped the scientific research, which is not plausible, the knowledge gathered so far must be enough to answer the questions: what is life as a physical phenomenon? how can we build artificial life?

The phenomena related to quantum uncertainty are the only unusual ones that we have encountered at the atomic scales. There are no elementary phenomena that resemble concepts such as those that we call will, free will, intent, consciousness, thought, intellect, intelligence, reason, intuition, emotions, feelings, or the "subject", the "I". Such notions can be used as approximative descriptions of effects that involve collective phenomena.

The overall picture that emerges from the investigation carried out so far is consistent and does indicate that life is the amplification of quantum uncertainty from the microscopic scales to the macroscopic scales. From this idea it is possible to explain everything we know about life and start the endeavor that will lead to the creation of artificial life.

In general, the degree of quantum uncertainty decreases from the microscopic to the macroscopic scales, where the effects of the uncertainty principle tend to average to zero. Exceptions are precisely the living beings, which behave non deterministically in a deterministic environment. The amplification is possible only if nature is equipped with a suitable LAM, a ladder amplification mechanism, otherwise the probability is too small. A crucial property of the LAM is that it is sensitive to the tiniest variations of its own parameters, to the extent that it acts as a bifurcation, leaving just two possibilities: the universe is everywhere dead or alive wherever possible. Since (organic) life exists on earth, it must be equipped with a proper LAM and the universe must be alive everywhere possible.

Moreover, similar initial or boundary conditions must produce substantially similar results in comparable amounts of time, although the outcomes may differ in relatively minor aspects. Thus, we expect that every planet that is inhabitable by organic life does become inhabited in an amount of time comparable to the one taken by life on earth. Since the conditions for organic life are presumably met in a huge number of planets, we infer that by now more or less one planet per star hosts life forms substantially similar to ours. The other inhabitable planets host life forms unknown to us, depending on the diversities of their conditions.

The creation of artificial life is a major step of a new type of LAM for quantum uncertainty. The main challenge humans face is building sufficiently complex (but not necessarily specialized) Q-droids that can develop, produce and evolve themselves so efficiently to self-sustain and expand indefinitely. Some bright side, in the short run, might be the possibility to fund the research on the production and sale of relatively simple Q-toys for children and artificial pets for companionship.

We conclude with a few comments of broader interests. In a way, the uncertainty principle implies that the world is (almost) everywhere free at small distances, while it is (almost) everywhere enchained (by determinism) at large distances. Instead of being everywhere predictable (which might also mean boring, to be taken for granted, etc.), the universe hosts an eternal conflict between freedom and rule, with an apparent irreversibility along the direction of the relative distances: freedom decreases when the relative distances increase, while rule increases. The amplification of quantum uncertainty is an upstream journey against the current.

But there might be more, with consequences that have yet to be fully appreciated. Indeed, quantum gravity predicts the violation of microcausality [17]. At scales that are much smaller than the atomic ones, but still much larger than the Planck length, which might mean around $10^{-24}$-$10^{-27}$cm, the concepts of time, past, present and future, cause and effect lose meaning. It appears that these notions are not fundamental principles of nature, but effective descriptions that are good enough for a number of practical purposes. The breakdown of causality at small distances moves in a direction that is somewhat similar to the one opened up by quantum uncertainty: in some sense, it gives us another sign that the universe "does not want" to be subject to the chains we naively forged for it. One day, we might have to accept as a fact that the universe is indeed *alive*.


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